

SUBJECT: A Survey of Automated Scheduling
Models - Case 610

DATE: April 7, 1969

FROM: A. B. Baker

ABSTRACT

This memorandum reviews the current state-of-the-art in automated scheduling models. Descriptions and comparisons of seven scheduling models currently available in the aerospace industry are presented. Though each was constructed to satisfy a unique set of requirements, certain similarities of construction and methodology were noted: all of the models are organized into three distinct functional areas (Data Preparation, Scheduler, and Output), all use one of two generally accepted methods to produce crew timelines (sequential and window-filling) and all considered candidate tasks in descending order of priority. Dissimilarities in the models pointed up several problem areas in the construction of any activity scheduling model including the classification of input data, the criteria used to establish task priorities, and the necessity for a scheduler algorithm to be sensitive to human factors.

The report concludes with several recommendations for a new activity scheduler, including:

- a. that any new model be constructed in modules such that each of the basic functions are isolated from the rest of the model. This would facilitate evaluation of different techniques or algorithms in each area.
- b. ephemeris data be generated independent of an activity scheduling model where the capability to generate such data already exists, as in the BCMASP Earth-Orbit Simulator.
- c. that the model contain internal data libraries to simplify the input data decks for each computer run.

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MEMORANDUM FOR FILE

1.0 Introduction

The term "scheduling," as used in this memorandum, denotes the process whereby individual activities or operations to be performed during a mission are integrated into a flight plan or mission timeline. Flight scheduling for the relatively short duration missions in the Mercury, Gemini, and Apollo programs were performed manually. However, missions in the Apollo Applications Program (AAP) are to last for one to two months and missions of even longer duration are being planned in the post-AAP period. The increased duration of these missions will significantly increase the scheduling alternatives. It is this increase which provides the motivation for seeking to automate as much of the scheduling process as possible in order to: (1) reduce the burden of tedious manual scheduling, and (2) decrease the time required to construct detailed timelines.

Automated scheduling models have a wide spectrum of potential uses in all phases of any manned space program. In the early planning stages, such models could be used to confirm the feasibility of the proposed mission objectives by verifying the compatibility of manpower and equipment with operational and experimental requirements. They can also aid system and subsystem designers by providing operating profiles for various subsystems and by analyzing the effects of alternative designs on the mission. Prior to launch they can be used by flight operations planners to generate nominal flight plans for each crewman. Finally, such models could be used to update activity timelines in "real-time" during missions when off-nominal situations require revisions to the nominal schedule.

A large number of activity scheduling models have already been developed by the aerospace industry but since these programs have usually been developed for use in only one or two of the areas described above they vary quite markedly in capability and output. The purpose of this memorandum is therefore to review the current state-of-the-art in activity scheduling models. Section II presents descriptions of several existing activity scheduling models while Section III compares the construction and capabilities of these programs. Section IV presents recommendations for the synthesis of an automated scheduling model which could be used to support long duration missions.

2.0 Descriptions of Existing Scheduling Models

Table 1 presents a list of 18 computer scheduling models which, with one exception, are already in use in the aerospace industry. Documentation on these programs was found to be meager - so meager in fact that an intensive literature search turned up written reports on only 7 of the 18 models listed. This section presents summary descriptions of each of the 7 models for which documentation was found.

Though the models vary in complexity, flexibility, and capability, certain similarities in construction can be noted. All are organized into three distinct though not necessarily separate sections: Data Preparation, Scheduler, and Output. Minimally, the function of the Data Preparation section is to accept a variety of spacecraft, crew, and experiment data and to arrange it according to the needs of the Scheduler. It may, depending upon the particular model, perform a variety of additional functions such as establishing task priorities for all activities or analyzing the input data to determine whether or not a gross compatibility exists between the spacecraft/crew capabilities and the task requirements.

The Scheduler section contains the scheduling algorithm. Though each algorithm is unique, they generally follow one of two approaches: "sequential" timelining or timelining by "window-filling." In the sequential approach, timelines are constructed by scheduling activities in chronological order, i.e., in a way analogous to adding successive links to a chain. The selection of the individual activity - or link - to be scheduled at a particular time is accomplished by choosing the highest priority activity (from the group of activities which have not yet been scheduled) whose requirements can be met at that point in the timeline. The task having been scheduled, mission time is incremented by an amount equal to the time required for the task, and the process is repeated. The window-filling approach is the converse of the sequential approach. Each task is scheduled in descending order of priority by searching over the entire mission time until a time is found (usually the first opportunity) when the task requirements are compatible with the past, present, and future conditions already existing in the timeline.

The primary function of the Output section is to print out the timeline data for each crewman. Again, depending upon the model, there may be a number of different types of analyses performed to measure the efficiency of the timeline against different criteria (i.e., time utilization, scientific effectiveness, etc.).

In general, the documentation stressed three aspects of the computer models: the scheduling algorithm, the input data required, and the method of establishing task priorities. The contents of the descriptions which follow reflect this emphasis.

TABLE 1

ACTIVITY SCHEDULING MODELS

1. ACTNET (Activity Network); McDonnell Douglas[†]
- *2. CASP (Crew Activities Scheduling Program); General Electric
- *3. Experiments Scheduling Program; MSFC and Brown Engineering
- *4. Experiments Scheduling Program; TRW
5. FORRCAS (Formulation of Resource Requirements by Computer Assisted Scheduling Techniques); Lockheed[†]
- *6. Heuristic Timeline Program; Boeing Space Division
7. MASCO; North American Rockwell[†]
8. MATE (Mission Analysis Technique for Experiments); Boeing[†]
- *9. OPTIMA (Operations Planning Techniques for Integrated Missions Analyses); General Dynamics, Convair Division
10. P/S/A (Planning, Scheduling, and Resource Allocation); Mitre[†]
11. SAM (Scheduling Analysis Model); Martin Marietta
- *12. SAMMIE (Scheduling Analysis Model for Mission Integrated Experiments); Martin Marietta
13. SAMPL (Schedule Algorithm for Mission Planning); Bellcomm
14. SAMSON (System Analysis of Manned Space Operations); Lockheed[†]
15. SDOA (Systems Design and Operations Analysis); Lockheed[†]
- *16. Space Station Mission Simulation Model; General Dynamics, Fort Worth Division
17. SPEED (System Planning Effectiveness Evaluation Device); McDonnell Douglas[†]
18. TOPSIE; IBM

*Described in Section II

[†]Reference 14

2.1 CASP - Crew Activities Scheduling Program*
Apollo Systems Department, General Electric Company

The version of the Crew Activities Scheduling Program (CASP) described in Reference 1 is specifically designed to develop pre-mission "nominal" flight plans. In its present form the program can generate schedules for a maximum of three crewmen but can be expanded to handle larger crews. The program is controlled by an "executive computer routine" which serves as an interface between the user and the program. The executive routine organizes and selects the specific subroutines required for each mission time and task assignment assessment and allows for the incorporation of alternate or additional routines. A program operations flow diagram for the CASP is shown in Figure 1. It illustrates the types of input data required, the operations performed by the program, and the various output options.

2.1.1 Input Requirements

Four basic types of input data are required: trajectory information, a list of all activities with associated constraints and priority ratings, crew constraints, and the operational capability of the spacecraft and its significant subsystems (i.e., power, thermal, attitude control, etc.). Crew activities are divided into four different classes of tasks:

- a. Flight Mechanics - those tasks directly concerned with orbital maneuvers.
- b. System Operations - including spacecraft "housekeeping" tasks such as communications, navigation, and system status checks.
- c. Personal Activities - eating, sleeping, rest, and personal hygiene.
- d. Experiment Activities - those tasks related to the performance of scientific experiments.

This system is intended to permit the reduction of heterogeneous activities into specific classifications to which a numeric priority system as well as other quantitative rules can be applied. Priority ratings in the CASP model are applied to classes of tasks as well as tasks within a class.

* Reference 1

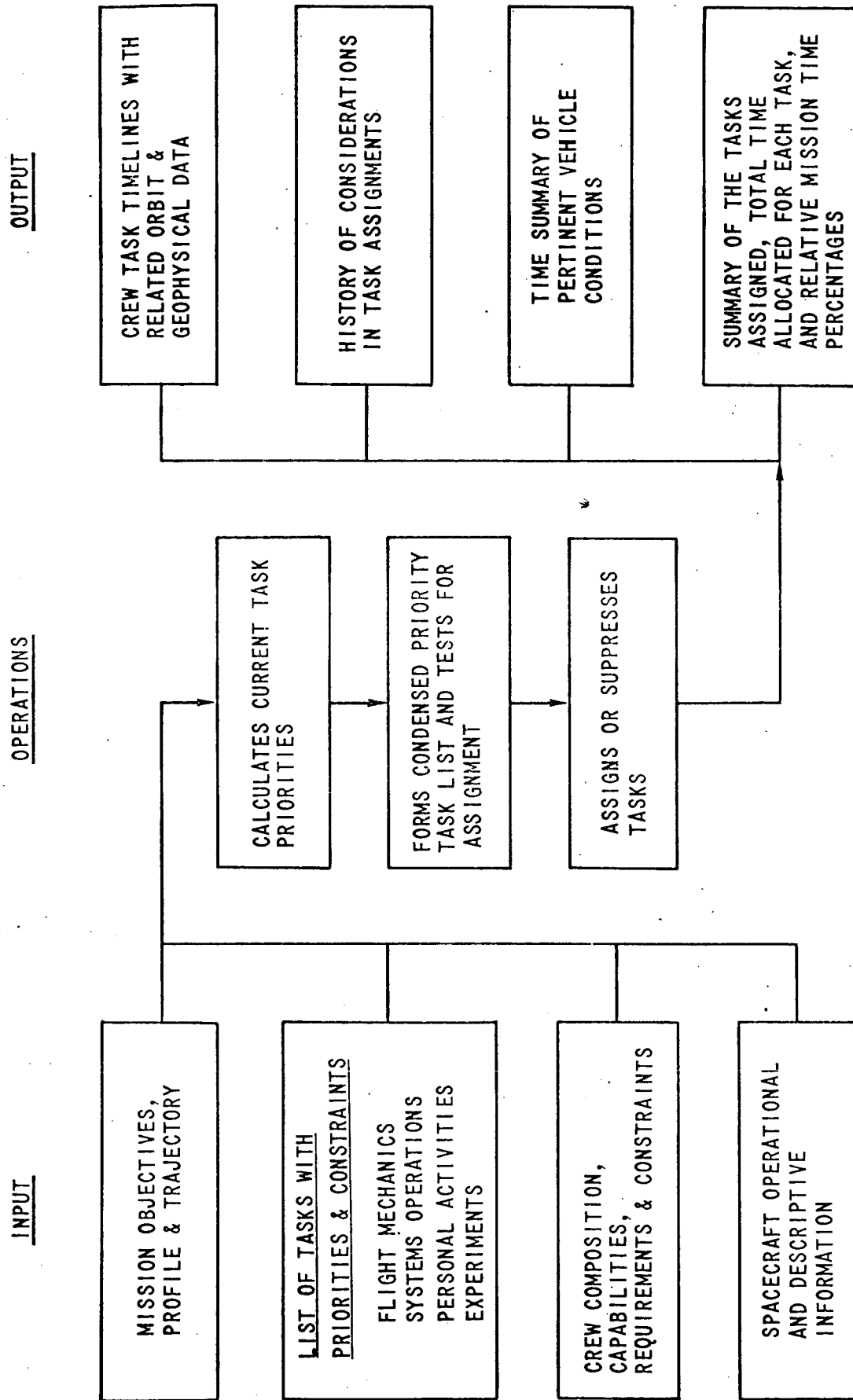


FIGURE 1 - PROGRAM OPERATIONS FLOW DIAGRAM FOR THE CREW ACTIVITIES SCHEDULING PROGRAM*

*REPRODUCED FROM REFERENCE 1

2.1.2 Operations

The operational approach to activity scheduling used by the CASP is a continuously iterative process in which the priorities of all tasks are calculated and then the task requirements are tested against the existing constraints in descending order of priority. The first task consistent with all of the existing constraints is scheduled. It should be noted that the CASP program schedules by sequential assignment rather than by window-filling, though a "look-ahead" capability is included to assure that the task assignment will not conflict with future tasks. Recalculation of task priority at each iteration is necessary because the CASP provides for a time-varying priority for many tasks, especially those concerned with the crew's personal activities. For example, the priority of a "sleeping task" or "eating task" will increase as the time from the last execution of that particular task increases. In addition, a fatigue increment is associated with each task and a rest period is scheduled for a crewman when his accumulated fatigue level reaches the specified threshold.

Constraints are divided into three groups: relationships between tasks and between tasks and mission events; subsystem and equipment capability; and crew capability. After all of the unscheduled tasks have been arranged in order of their current priority, they are tested against the first set of constraints - i.e., those relating to previously scheduled tasks, the spacecraft ephemeris, and other mission events. Those tasks that are compatible with this set of constraints form a "condensed task list." The requirements for the tasks on this condensed list are tested for compatibility with subsystem and equipment limitations. The tasks compatible with these limitations are tested for compatibility with crew availability. The task of highest priority which is compatible with all three classes of constraints is scheduled.

2.1.3 Output Options

Output schedules are available on four levels of detail. The first level provides mission time, ground station contact, vehicle day/night cycles, orbit number, task name and identification number, task duration, the role of the crewmen and the location of the performance of the task. The second level merely spaces adjacent listings proportional to the duration of the respective tasks to form a graphic crew timeline. The third level provides all of the previous information, but adds the fatigue level of each crewman at the completion of a task, task cycle time, fuel consumption, power requirements and data accumulation. Level 4 is intended for detailed scheduling analysis and shows the "basic factors" considered at the time

of each task assignment. In addition, summary statistics are printed at the end of each 24-hour period which show the total time and percent of mission time spent for all activities, the number of experiment phases assigned to each crewman, the number of those phases which were completed and the number which were interrupted.

2.1.4 Comments

One impressive feature of the CASP is its cognizance of the importance of human factors when generating a crew activity schedule. This is manifested in its consideration of crew fatigue and by an attempt to schedule tasks with sufficient variety to avoid boredom and decreased performance. Though it was stated that both these factors were considered, no mention was made of how the fatigue threshold or the criteria used to assign fatigue factors to specific tasks were established. Likewise, no details were given on how the scheduling of tasks was manipulated to relieve boredom.

The CASP was specifically developed for use as a pre-launch tool for developing nominal crew activity schedules but is being modified for use as a real-time tool in contingency planning. The reasons for its present limitation to pre-launch planning are not clear. No mention is made of program size or running time though one may infer from the description that both are quite large.

2.2 Experiment Scheduling and Compatibility Analysis Model for Earth or Planetary Orbit^{*} MSFC and the Brown Engineering Company

2.2.1 Input Program

The scheduling procedure is accomplished by running three computer programs in sequence. The first of the three programs is the Experiment and Astronaut Input Program. Its function is to process and sort input data, establish daily astronaut schedules (i.e., sleep, eating, and rest periods) and to schedule Inertial Measurement Unit (IMU) alignments and system status checks. Finally, it establishes the priority in which the experiments are to be scheduled. Inputs to this program include mission duration, number of astronauts and the activity cycle of each, spacecraft resources (weight, pressurized and unpressurized volume, power, data transmission rate and data storage capacity), and data on each experiment.

The input data required for each experiment is listed in Table 2. "Utility Value" is a number which indicates the relative priority of the experiment. Experiments may be input in the priority desired by the user or the preferential order may be established by the program itself using any of a number of different criteria (i.e., astronaut time, weight, power, etc.). The experiment tasks are broken down into three parts: setup, run, and teardown which permits more accurate scheduling if different levels of astronaut participation are required in each of these phases. In addition, an equipment number is assigned only to apparatus which is to be used for more than one experiment. The equipment number is designated as part of the experiment input data and a check is provided in the program to insure that there is no equipment conflict when scheduling the particular experiments which use that piece of equipment.

The input program prints out the information listed in Table 3. This information is also put onto magnetic tape so that it may be used as the input to the Activities Scheduling Program which establishes specific start and finish times for experiments and all other activities. The program schedules one mission day at a time in chronological order beginning with the first mission day.

2.2.2 Scheduling Procedure

After reading off the astronaut fixed schedules (including system status checks and IMU alignments) for the ith day from the input tape, the program checks each experiment in descending order of priority until it finds one which has not

^{*}Reference 2

TABLE 2

EXPERIMENT INPUT DATA TO THE
EXPERIMENT AND ASTRONAUT INPUT PROGRAM

- Experiment code
- Experiment number
- Early start time (in days, hours, and minutes)
- Late finish time (in days, hours, and minutes)
- Utility value
- Setup time required
- Run time required
- Teardown time required
- Number of astronauts required
- Specific astronaut designated to run the experiment (if desired)
- Equipment number (if this equipment is also used for other experiments)
- Weight of equipment required
- Pressurized volume required for equipment storage
- Unpressurized volume required for equipment storage
- Average power required during the setup, run, and teardown time of the experiment
- Rate at which data are generated (if the data are handled by the central data handling system)
- Ephemeris requirements

TABLE 3

OUTPUT FROM THE EXPERIMENT AND ASTRONAUT INPUT PROGRAMSpacecraft Information

- Total weight available for experiments
- Total pressurized volume available for experiments
- Total unpressurized volume available for experiments
- Average power available for experiments
- Maximum data transmission rate
- Maximum data storage capacity

Mission and Experiments

- Number of astronauts available for work
- Mission length
- Number of experiments submitted for scheduling
- Total weight required for all experiments
- Total man-hours required for all experiments
- Total power required for all experiments
- Total bits of information to be collected
- Total unpressurized volume used
- Total pressurized volume used
- Number of ephemeris experiments
- Maximum experiment running time

been scheduled. If the duration bounded by the start and finish times for the experiment does not include the ith day, the program continues its search. If the ith day is included, a check is made to determine if the experiment is ephemeris-bound; if it is, another subroutine determines when, if any, opportunities for performance will occur on the ith day. If no opportunities are found, the experiment search continues. Astronaut availability is determined next by noting if the astronaut is available at any time during the time specified for the performance of the experiment. If no astronaut is available the effort on that experiment is terminated and the search continues. If astronaut time is available, a check is made on electrical power and equipment availability. If all of the scheduling requirements are met, the time is entered onto the astronaut's schedule, the experiment is marked as having been scheduled, and the search continues. When there is no more time available on the ith day, the astronauts' schedule for that day is considered final and is transferred from core storage to an output tape. The input tape is rewound and the process begins again for the day i+1.

When schedules have been completed for all of the mission days, the weight and volume for all scheduled experiments is checked to make certain that the overall limits have not been exceeded. If they have, the program eliminates experiments of lowest priority until the physical characteristics are within the defined limits.

2.2.3 Output Program

The Output Program reads a tape generated by the Activity Scheduling Program and prints a mission summary showing the times each experiment is to begin and end and which astronaut is assigned to conduct it. In addition, it schedules periods of data transmission and prints out the transmission times and a running total of the amount of data in storage at any particular time.

2.2.4 Comments

The flexibility of the window-filling technique is offset by limiting the consideration of scheduling alternatives to one 24 hour period at a time. A more efficient timeline could be derived if the entire mission time were considered at each scheduling attempt.

The efficiency of the output timeline as well as the operation of the model could be improved by performing the check of experiment weights and volumes before any time-lining has been performed. Eliminating the lowest priority experiments after the schedules have been established leaves holes in the astronauts' timelines, which may reduce the efficiency of the schedule. Also the computer run might be significantly shortened if the need to schedule several experiments were eliminated prior to the beginning of the scheduling process.

2.3 Experiments Scheduling Program, A Proposed Approach^{*} TRW Systems

It should be noted at the outset that what is described below is a concept or a proposed approach and not a working model. The approach has been developed through the preliminary definition phase but further work has been suspended pending decisions from MSC as to their specific requirements for a scheduling model.

The model is divided into three "modules." The Pre-processor Module processes the input data into a form acceptable to the Scheduler Module. The latter generates the actual activity timelines while the Output Module collates the data and outputs a variety of summary information. A functional flow diagram of the entire model, shown in Figure 2, gives the detailed functions of each module and illustrates their inter-relationships.

2.3.1 Input Data Requirements

As the figure shows, basic input data falls into one of four general categories. The Resource Definitions include a variety of data which describe the characteristics of the spacecraft, crew, and four major subsystems (attitude control, data handling, electrical power, and environmental control). Crew data consists of astronaut duty cycles and the characteristics of the basic tasks defined in that cycle. The latter include activity start time, metabolic level (astronaut's level of exertion), station location, and station lighting conditions. Run Control Variables control the operation of the model. They include flags which control such decisions as the resources to be considered in the scheduling process and the type of output data required. Also included are values of total mission time and the incremental time interval (the smallest unit of time considered for the scheduling process).

An elaborate set of definitions is presented in References 3 and 4 which describes the activities or tasks used in this model. EXOP is a designation for an entire experiment or operation including repetitions. The EXOP consists of one or more activity groups, each of which is a group of activities or tasks within the EXOP which must be performed in a specified sequence and within defined time intervals of each other. The requirements of each experiment or EXOP are also read into the Preprocessor. Included in the input data are the experiment rating or desirability factor (explained below), number of repeat cycles along with earliest start and latest end times of all required repetitions, the manpower, system, trajectory, and equipment requirements, and the activity groups and specific tasks which make up the EXOP.

^{*}References 3 and 4

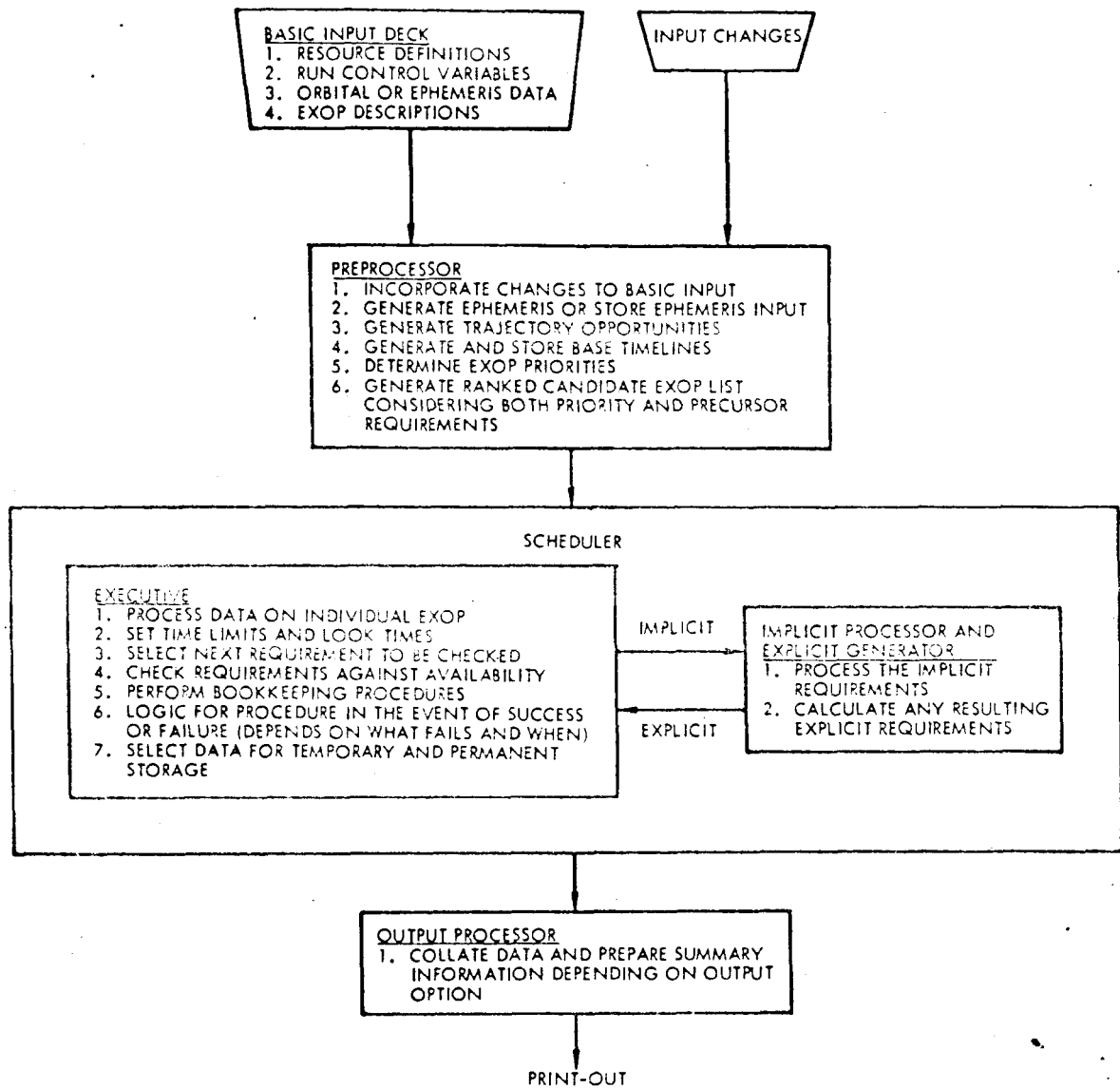


FIGURE 2 - FUNCTIONAL FLOW DIAGRAM FOR THE TRW
EXPERIMENTS SCHEDULING PROGRAM*

*REPRODUCED FROM REFERENCE 3

2.3.2 Preprocessor Module

The implementation details of the Preprocessor module have not been formulated yet. However the module has four main functions:

- a. To generate a spacecraft ephemeris or to store input ephemeris data. An option may be provided so that the same ephemeris will not have to be generated more than once. It may be stored on tape when generated and supplied as input to subsequent runs requiring the same ephemeris.
- b. To determine all line-of-site contacts for all ground stations and photographic targets from the ephemeris data.
- c. To determine the relative priority of each EXOP and to then rank the EXOPs in descending order of priority. The method of establishing activity priorities is rather subjective and vague. Priorities are established in order to permit a choice between two or more activities which are competing for spacecraft resources at a given instant of time. The priorities are a function of both the "desirability or inherent worth" of an activity and the difficulty of the activity. The desirability factor takes the form of an input value assigned to each experiment or operation. The difficulty factor is a function of the activity requirements and is calculated internally. The latter considers
 - Performance restrictions imposed by the spacecraft ephemeris.
 - The required level of crew participation.
 - The ratio of each subsystem requirement to the normal capability of that subsystem.
 - Equipment requirements.
 - Number of repeat cycles required.

These and other factors are rated numerically and combined in weighted form to express the relative difficulty of the activity. Finally the priority rating is set equal to the product of the desirability and difficulty factors.

- d. To rearrange the Resource Definition data into a base timeline for each crewman, which is the basic input to the Scheduler Module. Initially the base timeline will contain only the crew and housekeeping cycles which were input

to the Preprocessor Module. However, the timeline will be updated by the Scheduler Model as each experiment is scheduled so that at any point in the scheduling procedure, it will reflect the commitments resulting from all activities which have already been scheduled.

2.3.3 Scheduler Module

The EXOP requirements which must be considered when an EXOP is a candidate for scheduling are assumed to fall into two classes - explicit and implicit. An explicit requirement is "a demand that is stated in terms of the same 'units' as the affected resource or condition,"* while an implicit requirement is "a demand that is most easily (or can only be) stated indirectly and thus must be processed to check compatibility."* Examples of both types of requirements are given in Table 4. The scheduling logic provides that any conflict between the requirements of a candidate EXOP and commitments already in the base timeline must be resolved in favor of the latter since by definition these commitments represent requirements of higher priority. If the EXOP cannot be scheduled anywhere in the timeline it is simply cancelled and removed from the list of candidate EXOPs.

The primary component of the Scheduler Module is the Executive model which processes all of the candidate EXOPs. The model first sets up a "temporary" timeline by duplicating the current base timeline. It locates the first opportunity at which the explicit requirements of the EXOP's first Activity Group are compatible with the current commitments. Control is then transferred to the Implicit Processor and Explicit Generator (IPEG) which contains "dynamic limit line" models of four major subsystems: attitude control, data handling, electrical power, and environmental control. Each of these models investigates the compatibility of the Activity Group requirements with the capabilities of the subsystem. If they are compatible, the Activity Group is inserted in the temporary timeline and the compatibility of requirements and commitments for the EXOP's next Activity Group is similarly investigated. A unique feature of the scheduler logic is the capability of the subsystem models in the IPEG to check not only the present capabilities of the subsystem in relation to the activity requirement but to also consider the future or "downstream" effect on its capability (and hence on the present commitments which are downstream in mission time) of placing the activity at that particular place in the timeline. When acceptable scheduling opportunities have been located for all Activity Groups in the EXOP, the EXOP is scheduled by making the resultant temporary timeline the new

* Reference 3

TABLE 4a

EXOP Explicit Requirements

- Number of Astronauts
- Astronaut Station Location
- Station Lighting
- Astronaut Metabolic Limits
- Special Equipment Required
- Trajectory Requirements

TABLE 4b

EXOP Implicit Requirements

- Attitude and Attitude Hold Mode
- Data Handling and Communication
- Electrical Power
- Environmental Control and Life Support

base timeline. The EXOP is then removed from the list of candidate EXOPs and the procedure begins again. The procedure is repeated until all candidate EXOPs have been considered.

2.3.4 Output Processor Module

Details of the Output Processor Module have not been formulated. It is anticipated that it will have several options available so that it could provide different information and/or the same information in different formats.

2.4 Heuristic Timeline Program^{*}

Space Division, The Boeing Company

The Heuristic Timeline Program described in Reference 5 was developed to perform timeline scheduling for a large multi-purpose space station with a maximum of 30 crewmen. The report gives a rather vague description of the program's operation and capabilities, but does supply the functional flow diagram of the scheduling model which is reproduced in Figure 3. Note that the model is a single program and cannot be used to derive different levels of detail. Every change in input data requires that the entire program be run again. This can be quite costly since Boeing has indicated that the program requires a long running time.

2.4.1 Program Inputs

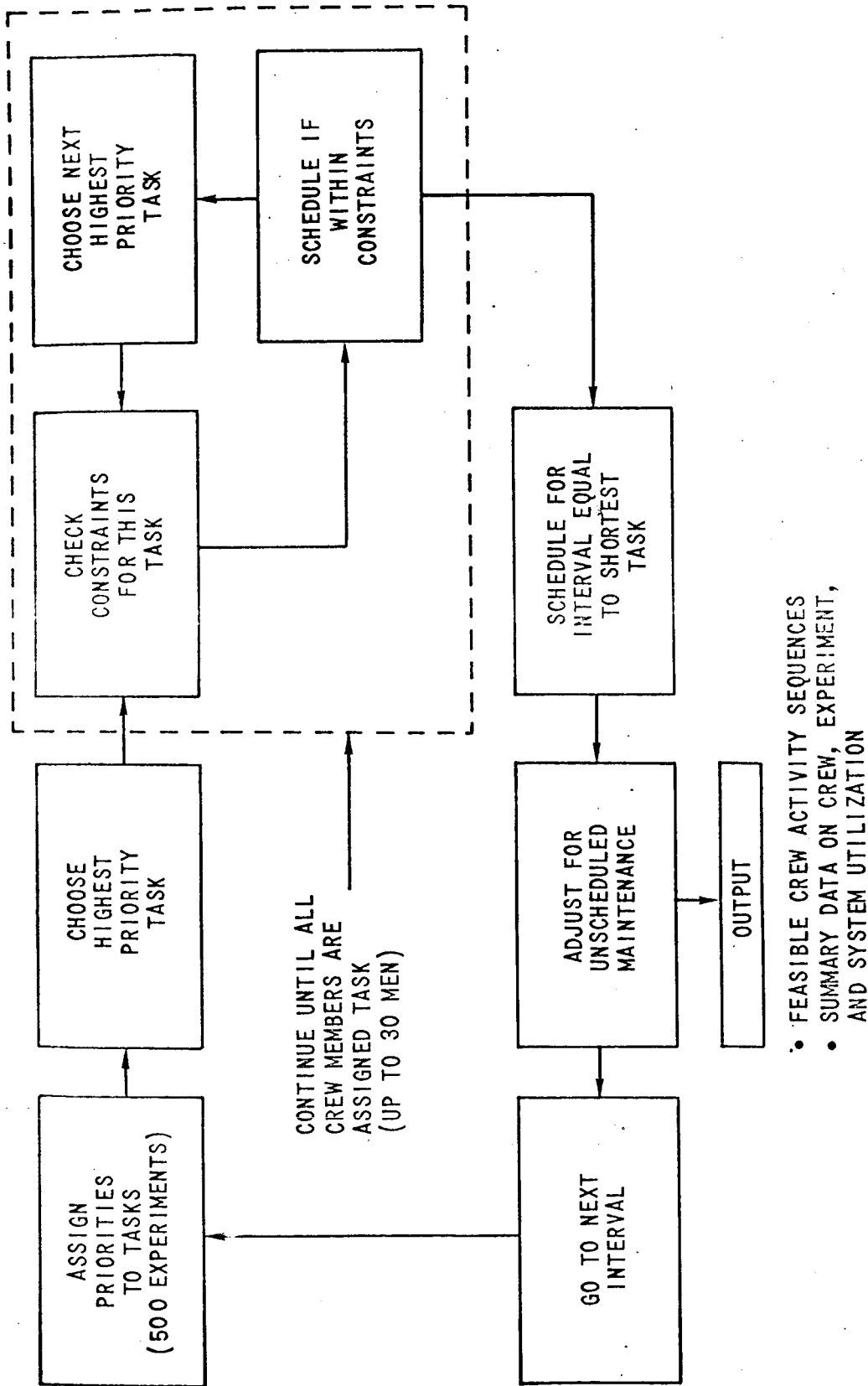
The program's degree of sophistication can be inferred from the required input data. These are shown in Table 5. The crew schedule information includes the nominal time at which each crew member performs his daily tasks and the duration of these tasks. Though they are usually scheduled at the same time every day, the performance time is allowed to vary within ± 2 hours to provide some flexibility in scheduling long duration or ephemeris-bound experiments. All crewmen are assigned to one of three overlapping shifts which permits continuous station operation. Each crewman is assigned primary and secondary skills so that two backup crewmen are available to assist the primary crewman responsible for each experiment category.

Scheduled maintenance tasks are the regular systems housekeeping tasks which can be scheduled in advance. They are input as a daily activity. Unscheduled maintenance represents repair of equipment failures. The occurrence of these failures is generated by a Monte Carlo simulation of the mission in another program and is read into the Timeline Program as discrete data. The latter consists of the type of failure, repair time, the crewman capable of making the repair, the urgency of making the repair, and any experiments which cannot be performed until the repair is completed.

2.4.2 Scheduler Algorithm

All of the characteristics shown in Table 5 are considered when scheduling an experiment. Though not clearly defined, the model apparently has some provision for determining spacecraft-target encounters and the lighting conditions during these encounters. There is also no mention of whether a single

^{*}Reference 5



- FEASIBLE CREW ACTIVITY SEQUENCES
- SUMMARY DATA ON CREW, EXPERIMENT, AND SYSTEM UTILIZATION

FIGURE 3 - CREW ACTIVITY SCHEDULING LOGIC FOR THE BOEING HEURISTIC TIMELINE PROGRAM*

*REPRODUCED FROM REFERENCE 5

TABLE 5REQUIRED INPUTS TO THE HEURISTIC TIMELINE PROGRAM

- Basic Crew Schedules
- Crew Skills
- Maintenance Inputs
 - Scheduled Maintenance
 - Unscheduled Maintenance
- Experiment Characteristics
 - Experiment Category
 - Number of Repetitions
 - Duration of each Repetition
 - Minimum and Maximum Time between Repetitions
 - Earliest Mission Time for the First Performance
 - Latest Mission Time for the Last Performance
 - Crew Skills Required
 - Periodic Monitoring Required
 - Equipment Required
 - Predecessor Experiment Required
 - Ground Targets Required
 - Spacecraft and Target Lighting Conditions
 - Quantity of Data Generated per Repetition
 - Power Required

computer run schedules an entire mission or only a fraction of it. Since the program is able to schedule the activities of up to 30 crewmen, it is highly likely that it schedules less than the total mission time, perhaps 24 hours.

The personal and system housekeeping schedules are blocked out before the scheduling process begins. At each succeeding available time interval, the program first assigns priorities to all of the unscheduled tasks. Then, beginning with the highest priority task, it checks the requirements of each task until it finds one whose requirement are compatible with the existing conditions. The task is scheduled, time is increased to the next available time interval, and the process begins again. The program continues in this manner until all available time is exhausted.

2.4.3 Program Output

There appear to be no output options. The only output mentioned is a very detailed mission timeline which shows all the activities in sequential mission time along with a complete description of the activity. The latter would include (where applicable) the mission time, task, crewmen assigned, data stored (or transmitted), electrical power, attitude propellant required and finally, the ground site being observed. Apparently the program does no other summary analyses.

2.5 OPTIMA - Operations Planning Techniques for Integrated
Missions Analysis*
Convair Division, General Dynamics Corporation

2.5.1 System Description

A functional flow diagram of the OPTIMA System is shown in Figure 4. Data is input through the Scheduling Model Program which is an engineering description of the mission. It includes scheduling criteria, crew capabilities and constraints, orbital parameters, target and communication network characteristics, task and subsystem descriptions, resource constraints, and any other mission constraints which affect scheduling. All changes in mission characteristics are made in the program; no changes are required in the other programs. The Down-Translator and Preprocessor-Editor programs encode the model and establish the necessary arrays. The latter also eliminates those portions of the model it will not need without disrupting the remainder of the model.

The Orbit Drive Program accepts inputs in the form of orbital parameters, target characteristics, etc., from the Scheduling Model Program and generates spacecraft ephemeris data. The output is a timeline of opportunities for target acquisition and communication.

The Discrete Network Simulator is the heart of the system. The simulator permits the scheduling of systems of discrete activities and enables these systems to be studied as a function of time by using a variable time base which automatically adapts the time-base resolution to the characteristics of each discrete function. Task assignments are made on the basis of predetermined priorities (discussed below) but provision is made to schedule ephemeris-bound tasks first. A running check is maintained on the status and utilization of equipment and resources.

Finally, three programs are used to organize the output data. Outputs include crew schedules, instantaneous and cumulative expendables consumption, and performance statistics.

2.5.2 Establishment of Task Priorities

The program utilizes a concept of static and dynamic priorities. Performing a specific task at a specified time is "not only a function of the intrinsic value of performing the task (priority in the usual sense), but is also related to the

* Reference 6

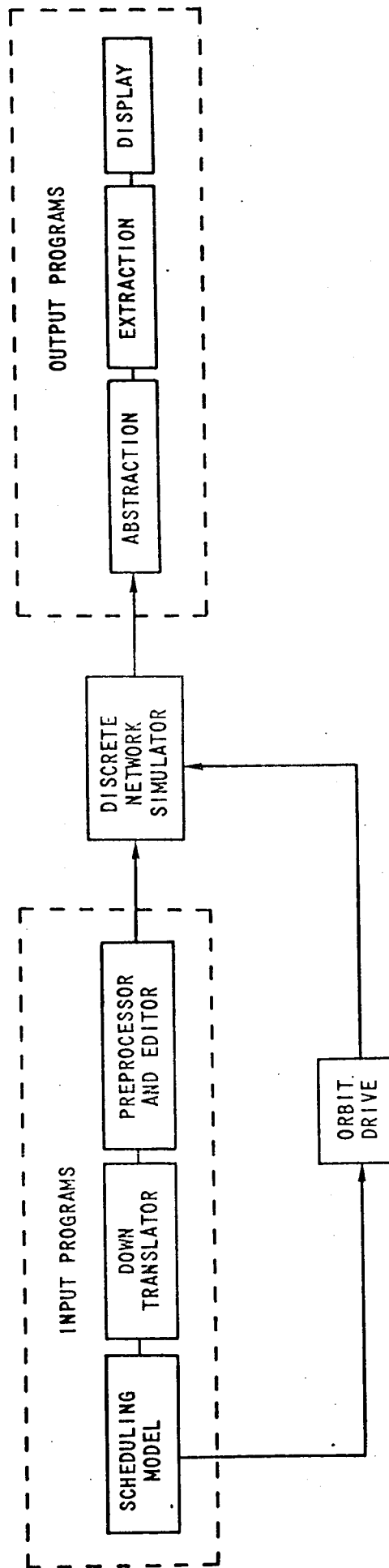


FIGURE 4 - FUNCTIONAL FLOW DIAGRAM FOR THE OPTIMA SCHEDULING PROGRAM

past history within the mission, the current status of crew members equipment and resources, and future predictions of opportunities vs requirements and resources." The total priority is established by using a combination of the static and dynamic factors listed in Table 6. The pacing function, P_z , contains a number of subfunctions including a sequencing function for related tasks, an alternator function to distribute repetitive tasks among crew members, and an "adaptive distribution function relating priority to the ratio of number of repetitive trials remaining to the number of opportunities remaining."

2.5.3 Comments

The paper describing the OPTIMA system lacks sufficient detail to make a meaningful evaluation of the approach. In addition, its use of terminology can be quite confusing. For example, it refers to the OPTIMA "system" as a set of individual "programs" but judging by the rest of the description, they appear to be no more than subroutines of one large program. There are no definite separations between programs as in the MSFC/Brown Engineering Experiments Scheduling Program (Paragraph 2.2).

Despite these shortcomings however, the program does have some interesting features, including:

- a. the capability to vary the astronaut work/rest cycles, and
- b. the capability to schedule on a variable time base.

The program can be used for mission planning, equipment design, and crew training. In addition it can be used for real-time analyses to investigate the effect of an unexpected deviation from the nominal mission on equipment parameters.

TABLE 6

STATIC AND DYNAMIC CRITERIA USED
TO ESTABLISH OVERALL TASK PRIORITY

$$P = f(P_N, P_E, P_{DQ}, P_V, P_P, P_R, P_O, P_Z),$$

P_N = Nominal ranking of tasks

P_E = Emergency ranking of tasks

P_{DQ} = Time-dependent priority, referenced to previous completion of task

P_V = Decreasing function after minimum mission objectives are satisfied

P_P = Value of performing a partial task within a restricted time period

P_R = Availability of resources (crew, power, data, attitude control, etc.)

P_O = Opportunity to perform task (tracker, target, sun angle, etc.)

P_Z = Pacing function

2.6 SAMMIE - Scheduling Analysis Model for Mission Integrated Experiments*

Martin Marietta Corporation

The model is primarily designed to schedule the performance of a well defined group of experiments subject to the constraints of crew availability and the compatibility of experiment requirements with spacecraft capability. The model was specifically intended to be a simple algorithm which sacrifices sophistication for computation speed. However, this results in a substantial amount of hand scheduling being performed prior to the computer run which must be presented to the model as input data. The model itself is approximately 150,000 words long and is written in FORTRAN.

2.6.1 Establishment of Timeline Constraints

The functional flow diagram of the model is shown in Figure 5. It illustrates the sequence in which data must be input to the model. The first input is a basic daily (24 hour) cycle for each crewman. The cycle is a constant for the entire mission. It contains the start and stop times of all personal, experimental, and housekeeping tasks which occur repetitively throughout the mission.

A schedule for major spacecraft operations (launch, rendezvous, reentry procedures) is input next. If conflicts with the basic crew cycle occur, the particular crew activity is truncated to permit insertion of the spacecraft operation. A crew rest schedule is input next. It presumes that certain days will be designated "rest days" which will consist of 24 hours of free time for all three crewmen in the sense that no experiments will be scheduled on rest days. Presumably, system housekeeping tasks and major spacecraft operations would still be performed.

Outside of the schedule for major spacecraft operations, the basic daily cycle can only be modified by supplying an entire new cycle for the particular day. Such modifications amount to an "overlay" of the basic cycle. In cases of extreme deviation from the basic cycle, the complete crew timelines for the days affected are generated by hand and supplied as input in their entirety. The last input then consists of prescheduled activities or overlay data which take preference over events already in the timeline. An existing activity is removed if the overlay activity covers more than 50% of it. If it covers less than 50%, the existing activity is truncated to allow room for the overlay. This feature can be used in a number of ways. For example, it allows predetermined schedules for particularly

*References 7 and 8

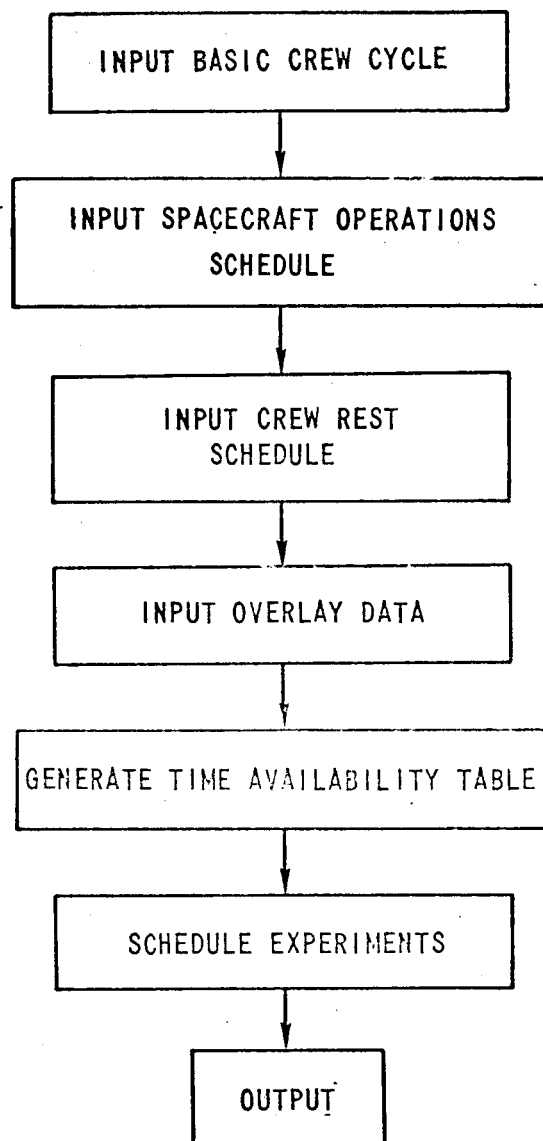


FIGURE 5 - SAMMIE FUNCTIONAL FLOW DIAGRAM

irregular mission days (i.e., the first few and last few mission days) to be inserted directly into the program. In the extreme, an entire schedule may be input as an overlay if the effect of adding one or two additional experiments is to be studied.

Using this timeline, a Daily Availability Table is generated by tabulating each astronaut's free time. Each day is broken up into 3 periods (0 to 6 hours, 6 to 14 hours and 14 to 24 hours are most commonly used though others may be defined by the user). The available time for each man in each period in each day is noted. The table provides a preliminary check for scheduling experiments.

2.6.2 Establishment of Experiment Scheduling Priorities

An experiment's scheduling priority is defined in terms of scheduling difficulty. Experiments are classified by group. The groups have a predefined order of scheduling priority and within each group, preference is given to experiment priority. In descending order of priority the experiment groups are:

- a. Experiments or activities which must be performed at specified mission times (i.e., ephemeris-bound experiments, EVA, spacecraft operations, rest days).
- b. Experiments which are in some way constrained or affected by other (non-scientific) activities.
- c. Activities which occupy large blocks of time (i.e., an entire morning or afternoon) and require two men.
- d. Cyclical experiments which repeat in particular sequences. Examples are
 - performance before, with, or after another activity,
 - performance at specific times or on particular days,
 - performance in a specific sequence,
 - performance by a particular astronaut, and
 - variable performance times and variable repetition intervals.
- e. "One-shot" experiments requiring two men.
- f. One man experiments.
- g. Unmanned experiments.

2.6.3 Scheduling of Experiments

The actual scheduling of a particular experiment is performed by one of three subroutines: Subroutine A is used for experiments whose performance is independent of other activities. These experiments may be "one-shot" or multiple performance type. Subroutines B and C are for special cases: Subroutine B is used for experiments which require particularly long performance times while Subroutine C is used for those experiments whose performance is tied to the performance of other experiments or activities. The subroutine to be used is an input to the program along with other experiment characteristics.

There are four types of activity start-time/window combinations available in Subroutine A. Type I is used when a specific start time and window are desired. That is, the experiment must be performed within Δt hours (the window) after some specific start time t_1 . This input may be used to specify the scheduling of a "one-shot" experiment anywhere in the mission by increasing the size of Δt to encompass the entire mission. It can also be used to specify repetitive performances which occur periodically by specifying separate start times and windows for each performance.

The remaining three types of start time/window performance specifications are variations of the multiple performance specification in Type I. Type II provides for a sequential set of performances to be completely within a specified amount of time. Type III is similar to Type II but permits the specification of a uniform length of time between performances. Finally, Type IV allows the scheduling of two or more performances within a given time measured from a previous performance.

As stated above, Subroutine B is used to schedule experiments which have particularly long performance times. The subroutine searches the Time Availability Table to find a block of free time which is compatible with both the specified required time and other operational constraints. It schedules the experiments in time-blocks of uniform length and so finds the integral number of time-blocks in the test block and, if the remaining experiment time is less than the time remaining in the last test block, the experiment is scheduled.

Subroutine C is used to schedule experiments either before, after, or concurrently with another activity. These requirements are input to the program as experiment characteristics. In the first two options (designated BEFORE and AFTER), the minimum amount of time between the performance of the independent and dependent experiments is also specified as an input. The "WITH" option is used only when the dependent experiment will not add significant performance time to the independent experiment.

One particular limitation common to all of the sub-routines is the inability to distinguish different time requirements for crewmen involved in an activity. When more than one crewman is required for an experiment, the program presumes they are engaged in that experiment simultaneously. Where this presumption is not valid, as in some AAP medical experiments, the "packing density" of experiments in the timeline generated by SAMMIE may be less than that achievable by hand-scheduling. This limitation can in some cases be reduced by hand-scheduling two or more experiments to SAMMIE as a unit. The user of SAMMIE must therefore be as familiar with experiments as the hand-scheduler to make the most effective use of SAMMIE.

2.6.4 Program Output

The program's primary output is a timeline of the mission, which includes a step-by-step account of each astronaut's activities. In addition, the program can print a variety of summary tables which illustrate the efficiency of the schedule.

2.7 Space Station Mission Simulation Mathematical Model*

Fort Worth Division, General Dynamics Corporation

The Space Station Mission Simulation Mathematical Model is capable of performing a variety of mission analyses and trade-off studies on three different levels of detail. It has the capability to

- a. Evaluate variable work periods and effects of rotating crew assignments.
- b. Provide trade-off data for use in studying effects of system interaction.
- c. Assess the effects on the mission of modifying or changing systems characteristics.
- d. Perform Resource Allocation Analyses.
- e. Generate crew activity timelines.

The structure of the model permits a great deal of flexibility. The model consists of three submodels, the Preliminary Requirements Model (PRM), the Planning Model (PM) and the Mission Simulation Model (MSM), which correspond to the three levels of detail. When used sequentially, they perform initial mission planning, generate a nominal mission plan, and then simulate the actual mission based upon that plan. Each of the models may be run separately and will yield pertinent intermediate results on a level of confidence commensurate with the corresponding level of input data. In addition, the model is so structured that the submodels, wherever applicable, use the same computer routines for the major functions. These functions include Crew Analysis, Experiment Analysis, Events Scheduling, Logistics Analysis, and Station Operations.

The model is used to simulate long-term space missions requiring crew rotation and logistics resupply by treating the interval between successive logistic launches as a single mission and using the vehicle and crew states at the end of the interval to reestablish these states at the beginning of the next interval. All of the models are written in FORTRAN IV and have reasonable running times (3-6 minutes, 8-25 minutes, and 20-45 minutes for the PRM, PM, and MSM respectively) on second-generation computers. Running time would probably be reduced on the Univac 1108 system.

* References 9, 10, and 11

2.7.1 Preliminary Requirements Model

The first of the three models is the Preliminary Requirements Model. It is designed to perform broad based analyses in relatively short run times to permit identification of feasible alternatives. It is used specifically to determine the width of the launch interval, the experiment payload, the crew skill mix, and initial task assignments for each crew member. A functional flow diagram of the PRM is shown in Figure 6.

2.7.1.1 Determination of Logistics Parameters

Data for the total multiphase mission is provided as input to the PRM. The logistics analysis routines are used to examine the input data to determine

- a. the duration of each launch interval, and
- b. the excess capacity of each logistics vehicle, which in turn determines the size of the experiment package for the particular launch interval.

The launch interval is determined from a variety of input data (e.g., usage rate of consumables). The experiment package is synthesized by adding experiments to the package until either the excess weight or volume associated with the particular logistics vehicle is consumed.

2.7.1.2 Determination of Crew Skill Mix

The crew skill matrix contains, for each astronaut assigned to the mission, one of three proficiency ratings (0, 1, or 2 corresponding to no proficiency, full proficiency and low-level proficiency) in each of 20 different skill categories. Corresponding estimates of required experiment time assume full proficiency. The program estimates the possible crew combinations for the particular mission phase in terms of their ability to perform the experiments for that phase. The crew combination which can complete the greatest number of experiment-hours in the least amount of time is chosen as the best for that launch interval.

2.7.1.3 Experiment Assignment and Schedule

The assignment of experiments to a particular crewman and the actual scheduling of the experiment are performed in two distinct steps. The experiments are first assigned to a particular crewman on the basis of the time and the skill

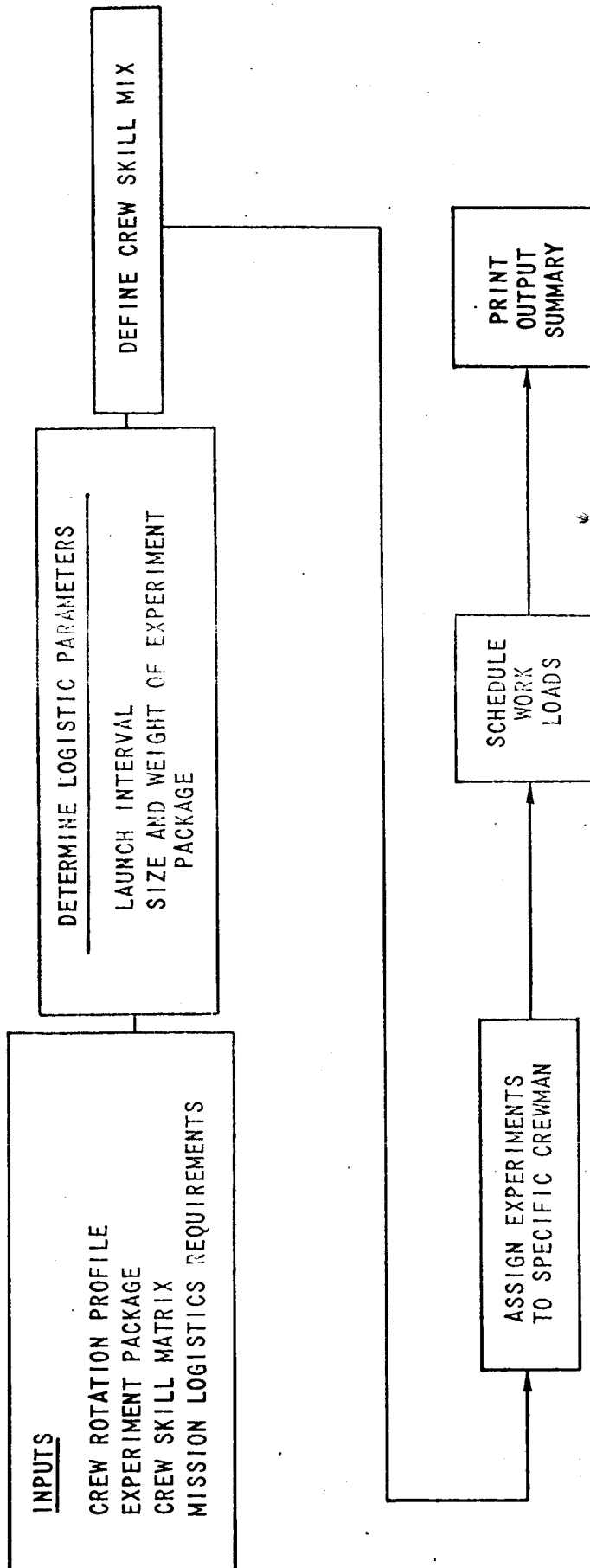


FIGURE 6 - FUNCTIONAL FLOW DIAGRAM FOR THE PRELIMINARY REQUIREMENTS MODEL

required to perform the experiment and the amount of time he has available for scientific work. The assignment procedure can be made using one of four methods:

- a. Equalize the total experimental man-hours of each crewman for the launch interval by assigning experiments with no associated priorities (the order in which the experiments are assigned is not specified).
- b. Equalize the total experimental man-hours per day for each crewman in the launch interval by assigning experiments with no priorities.
- c. Same as (a) except that the experiments must be assigned and scheduled in a specific order (priority method).
- d. Same as (b) except that the experiments must be assigned and scheduled in a specified order.

An experiment is assigned by noting the skill(s) it requires and searching for the man most proficient in that skill(s). However, this procedure may set up unequal man-hour loads thus preventing some experiments from being performed. An iterative process is therefore used in those cases to reassign experiments among the other crewmen with a slight penalty in crew proficiency.

Experiment Scheduling which follows the assignment procedure uses a "geometric" technique for fitting several small rectangles into a larger constraining rectangle. Each experiment is defined as a rectangle: the length of which is its duration in days and the height of which is the average number of hours per man per day required to conduct the experiment. The PRM arranges these small rectangles in an optimum order to fit them into a larger rectangle; the width of which is the duration of the launch interval and the height of which is the maximum number of hours per day that any crewman can devote to experimental tasks.

2.7.1.4 Outputs

The PRM prints out a variety of results for each launch interval including:

- a. A list of experiment tasks assigned to each crewman.
- b. Total number of hours worked by each crewman.
- c. Work remaining on each of the tasks.

- d. A number of effectiveness measures (fraction of total experiment work completed, fraction of available crew time utilized, etc.).

On option, the PRM will prepare four input decks to the Planning Model, the next submodel in the sequence.

2.7.2 Planning Model

The Planning Model uses the data developed by the PRM to generate a detailed nominal mission plan which includes schedules for all tasks and logistic requirements. A functional flow diagram of the Planning Model is shown in Figure 7. The referenced reports do not detail the differences between the PRM and the Planning Model except to say the latter offers considerable sophistication over the PRM. The PM uses the data supplied by the PRM along with its own library decks to produce a detailed schedule for a nominal mission. As in the PRM, the entire mission is viewed as a single problem. It first determines the logistics launch schedule, then generates crew schedules for station keeping, personal housekeeping and experiments. After the schedules are completed, the mission plan is evaluated by several evaluation routines. The program determines the resource profile, and evaluates the mission plan according to several different assessment indices. Finally, an option permits a tape of the final mission plan to be generated which is used as an input to the next phase.

2.7.3 Mission Simulation Model

The last of the three submodels is the Mission Simulation Model which simulates the actual mission formulated in the Planning Model from launch and unmanned checkout through the end of the mission. A functional diagram of the MSM appears in Figure 8.

The operation of the model is controlled by the Event Controller which is basically a mechanism for proceeding from event to event. The key feature of the model is its use of a Random Event Generator to insert unplanned events (i.e., crew illness, equipment failure, etc.) into the nominal schedule. The nominal mission plan is therefore being continually modified and updated to reflect the incorporation of these events into the schedule. The simulation concludes with a variety of summaries and evaluations.

2.7.4 Special Programs

In addition to the three basic programs, the model has a number of special purpose programs including a Crew Activity Timeline Program and an Experiment Analysis Program. In regard to the former it should be noted that the basic models

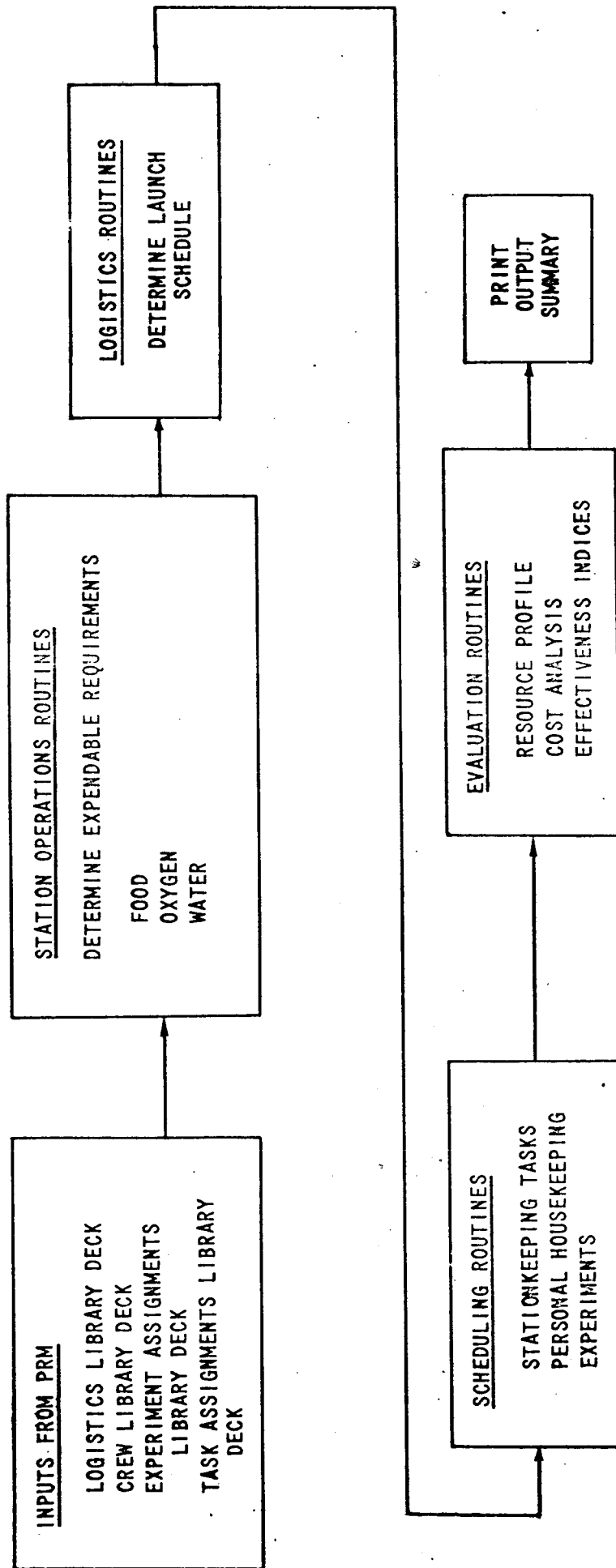


FIGURE 7 - FUNCTIONAL FLOW DIAGRAM FOR THE PLANNING MODEL

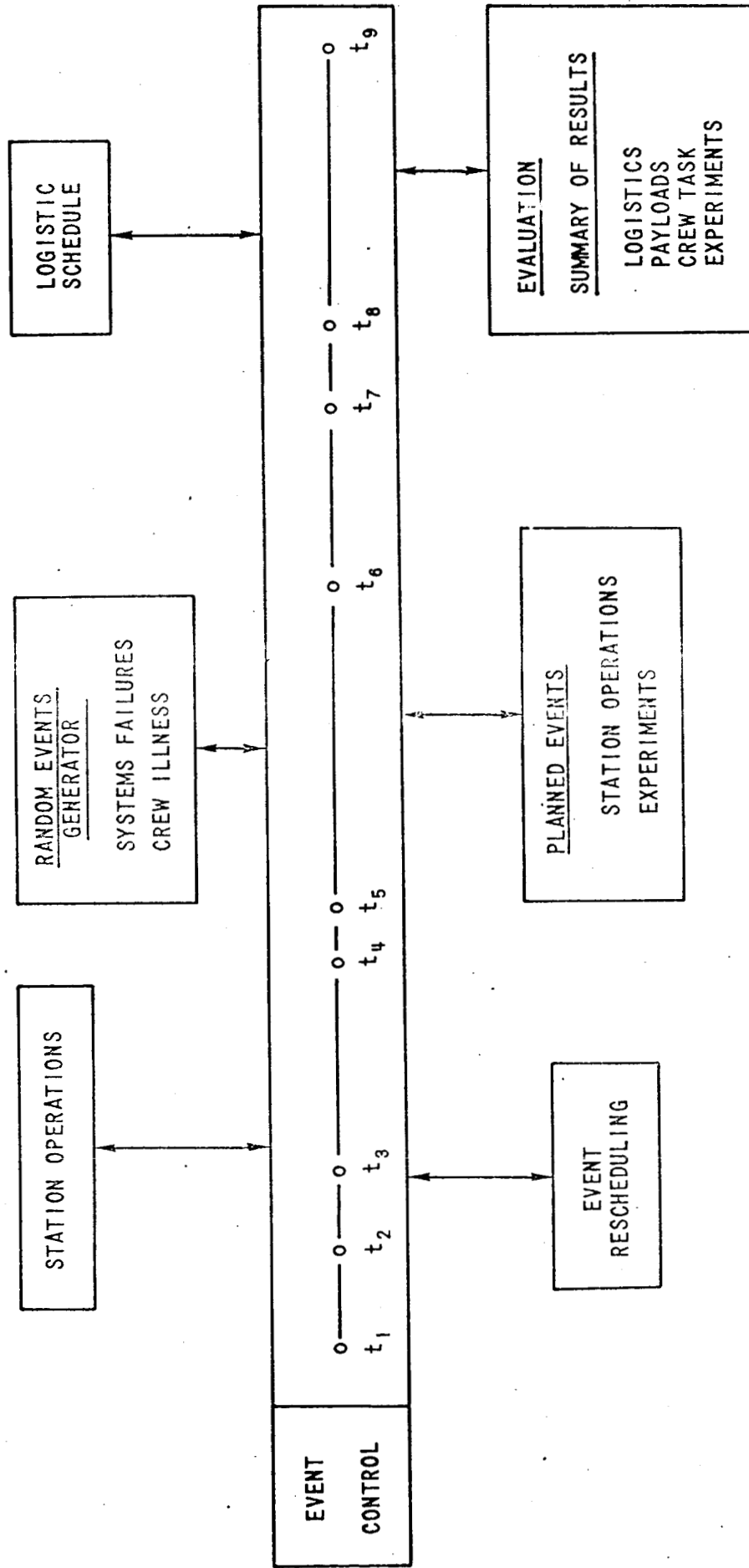


FIGURE 8 - FUNCTIONAL FLOW DIAGRAM FOR THE MISSION SIMULATION MODEL*

*REPRODUCED FROM REFERENCE 10

do "scheduling" but not "timelining." In all three models, events are scheduled into discrete time intervals of any desired length (24 hours is the most commonly used) but the events are not timelined within the interval. A separate Timeline Scheduler has recently been added to the model which, using the output of the Planning Model as an input, produces an activity timeline for each crewman. However, the Timeline Scheduler can only be used to schedule one day at a time. It must be rerun for each 24 hour period.

The Experiment Analysis Program is designed to overcome problems in program planning arising from incomplete or uncertain information about the proposed experiment package. The program uses available experiment data to generate experiment packages of different size and/or characteristics. The package can include "pseudo-experiments" which are not actual experiments but rather a set of experiment descriptors chosen by the computer. This technique permits a rapid analysis of proposed experiment packages. It can also use previously synthesized packages to perform a variety of sensitivity analyses designed to determine the effects of experiment mix on scientific accomplishment.

3.0 Comparison of Scheduling Models

As noted above, the automated scheduling models vary in capability, complexity, and flexibility despite their commonality of organization and input data requirements. While their similarities (discussed in Section 2.0) suggest a basic approach to activity scheduling, an examination of their dissimilarities is far more germane to an understanding of the different alternatives available to a potential user. Some of the more significant characteristics of each model are therefore compared in Table 7. The characteristics are divided into two distinct groups: the factors in the first group (labeled "Overall Model Structure") describe the overall structure of the model and how it operates while the second group (labeled "Task Assessment Parameters") consists of several factors which indicate the degree of sophistication of the scheduler algorithm.

3.1 Overall Model Structure

3.1.1 Number of Programs and Number of Output Options

In the first group, the number of computer programs in the model and the ability to choose different levels of output detail are a measure of the model's overall flexibility. While most of the models permit a choice of output data, only two, the MSFC Experiments Scheduling Program and the General Dynamics Space Station Mission Simulation Model, contain more than one program. In both, the programs must be run in a defined sequence to achieve the greatest level of detail. However, this is a relatively painless increase in complexity since all of the programs (excluding the first of course) prepare output tapes on option, which are used as inputs to the following program. The advantage of this construction is that it permits analysis on different levels of detail, thus tailoring its use more to the individual needs of the user and permitting significant savings in running time.

3.1.2 Contingency Analysis

There will undoubtedly be times during the mission when contingency situations will arise which will require deviations from the nominal schedule. Two of the more complex programs* simulate contingency situations by using Monte Carlo techniques and known failure rate data to simulate random

* Boeing's Heuristic Timeline Program and General Dynamics' Space Station Mission Simulation Model

TABLE 7
COMPARISON OF AUTOMATED SCHEDULING MODELS*

MODEL	SOURCE	OVERALL MODEL STRUCTURE				TASK ASSESSMENT PARAMETERS						VARIABLE CREW CYCLE
		# OF PROGRAMS	GENERATE EPHEMERIS	TYPE OF TIMELINING	CONINGENCY ANALYSIS	OUTPUT OPTIONS	TASK PRIORITY ASSIGNMENT	HUMAN FACTORS	CREW SKILLS	CREW LOCATION		
CREW ACTIVITIES SCHEDULING PROGRAM (CASP)	GENERAL ELECTRIC	1	NO	SEQUENTIAL	NO	4 LEVELS OF DETAIL	DYNAMIC	FATIGUE FACTOR	YES	I/A OR EVA ONLY	YES	
EXPERIMENTS SCHEDULING PROGRAM	MSFC/BROWN ENGINEERING	3	YES	*WINDOW-FILLING	NO	NO	STATIC	NO	NO	NO	NO	
EXPERIMENTS SCHEDULING PROGRAM	TRW	1	NO	*WINDOW-FILLING	NO	YES	STATIC	METABOLIC LIMITS	NO	YES	NO	
HEURISTIC TIMELINE PROGRAM	BOEING	1	NO	SEQUENTIAL	YES	NO	DYNAMIC	NO	YES	YES	LIMITED	
OPERATIONS PLANNING TECHNIQUES FOR INTEGRATED MISSIONS ANALYSES (OPTIMA)	GENERAL DYNAMICS, CONVAIR DIVISION	1	YES	SEQUENTIAL	NO	YES	DYNAMIC	ADAPTIVE WORK/REST CYCLES	YES	NO	NO	
SCHEDULING ANALYSIS MODEL FOR MISSION INTEGRATED EXPERIMENTS (SAMIE)	MARTIN MARIETTA	1	NO	WINDOW-FILLING	NO	YES	STATIC	NO	NO	YES	NO	
SPACE STATION MISSION SIMULATION MODEL	GENERAL DYNAMICS, FORT WORTH DIVISION	4	NO	*WINDOW-FILLING	YES	YES	STATIC	NO	YES	YES	NO	

* CONSIDERATION LIMITED TO ONE 24 HOUR DAY

failures. The Boeing model uses a separate computer program to generate failure data and provides this to the Activity Scheduling Model as input data. Maintenance time is then included in the crew timelines as required.

The General Dynamics Activity Scheduler uses failure rate data and Monte Carlo techniques to generate random failures in a Random Events Generator, which is part of the model's Mission Simulation Model. The latter inserts these random events into a previously determined nominal schedule and analyzes the effects on the efficiency of the schedule.

3.1.3 Spacecraft Ephemeris

All of the models utilize spacecraft ephemeris information to determine the time at which ephemeris-bound tasks must be performed. This information may take one of two basic forms: position data or time data. Two of the models* generate a spacecraft ephemeris from input orbit data and then compare the position of the spacecraft with the position of the required terrestrial target to determine whether a particular task is to be performed. These computations however are time consuming and are repeated during every run even if the input orbital data has not changed. An alternative is to determine the information in a separate computer program and then to provide as input to the activity scheduler only the specific mission times at which performance opportunities occur. The BCMASP Earth-Orbit Simulator (Reference 12) is designed specifically to investigate target site visibility from orbit and could be used to derive this information for a scheduling model.

3.2 Scheduler Algorithm

The significant characteristics of the activity scheduler algorithms are also compared in Table 7.

3.2.1 Task Priority Assignment

There are only two methods used to assign priorities to different tasks: static and dynamic. The word "static" is used to describe a method in which task priorities are assigned only once, before the scheduling process begins. The tasks are then scheduled anywhere over the mission duration by the window-filling technique. In this way, one is assured that any time which is available is already committed to a task which is of higher priority than any of the ones awaiting assignment.

*MSFC/Brown Engineering's Experiments Scheduling Program and General Dynamics' OPTIMA

The "dynamic" method is used with sequential time-lining (i.e., when tasks are scheduled in sequential mission time). The dynamic method requires that the task priorities be recalculated at the beginning of each uncommitted time interval. The tasks are then reviewed in descending order of priority until one is found whose requirements are compatible with the current capabilities of the spacecraft and crew. The task is scheduled, mission time is advanced by the time required for the task, and the process is repeated.

3.2.2 Crew Skills

The factors which are used to evaluate the compatibility of task requirements with the status of the spacecraft and crew are indicative of the sophistication of the scheduling algorithm. There are a number of basic factors which are used by virtually all scheduling models. These include task priority, crew availability, and the compatibility of consumables required and available.

This basic list is supplemented in each model by a number of different factors. The more significant ones are listed in Table 7. Though all of the models check crew availability, only four have the capability to differentiate particular crew skills. In this case, "crew availability" means only that the crewman (or crewmen) having the skills required to perform the task. If no crew member with the required skills is available, the task will not be scheduled. To provide greater flexibility, a variation of this approach assigns each crewman a numerical proficiency rating in all tasks. The program* then selects the most proficient crewman available (down to a predefined level) to perform the task. Again, if no crewman with sufficient skill is available, the task would not be scheduled.

3.2.3 Crew Location

All but two of the models consider the current physical location of each crewman when attempting to schedule a task. The method of accounting for location differs and in most cases was not explained. One very simple approach used by the CASP considers only whether the astronaut is inside or outside the spacecraft. Presumably this is an attempt to schedule as many experiments as possible during an EVA but in this case it seems like an unnecessarily complex approach since the experiments could simply be specified as a block of tasks which must be

* General Dynamics' Space Station Mission Simulation Model

performed in sequence. Note that the first tasks in this sequence would be the physical acts of donning the space suit and going outside the vehicle. Similarly, the final tasks in the sequence would be the physical acts of reentering the spacecraft and removing the space suit.

The other approaches were not discussed but there were indications that they were significantly more complex, and were able to keep track of the crewman's location throughout the spacecraft. Such information is used to minimize the amount of crew relocations required and to account for the time required for these relocations.

3.2.4 Variable Crew Cycles

Only two models* permit variations in the predefined schedule of the crewman's personal tasks (i.e., sleep/eat/rest cycle). The more common approach is to insert these tasks into the timeline before any other tasks are scheduled and to consider these cycles inviolate. However, in the two models noted, the scheduled performance time of these life cycle tasks can be adjusted within predefined limits (say ± 2 hours) when necessary to accommodate the scheduling of other tasks. This is a particularly advantageous capability which leads to better utilization of available time. It is also more closely related to the real world where one's personal schedule does indeed vary from day to day.

3.2.5 Human Factors

The exploratory nature and short duration of missions in the first three space programs neither permitted nor required that extensive consideration be given to crew factors other than those directly concerned with the astronauts' physical well-being. However, as indicated in Section 1.0, the AAP program will begin a new generation of missions which will be oriented much more toward scientific investigation than toward improving operational techniques or qualifying spacecraft equipment. Beginning with these missions, the astronauts' working conditions will more closely approximate those found at terrestrial scientific stations (e.g., separate working and living quarters, and freedom of movement throughout these quarters). Therefore the astronauts can be expected to encounter some of the human factors problems which are often experienced by the scientific staff at isolated stations. These problems are related to fatigue, boredom, isolation, small group interactions, confinement, etc.

* General Electric's CASP and Boeing's Heuristic Timeline Program

Of all the programs reviewed, only three attempted to take these problems into account. The CASP assigns a "fatigue factor" to each task. When assigning a task to a crewman it increases the crewman's total fatigue level by the fatigue factor associated with the task. The priority of a rest period for the crewman is then determined by comparing his current fatigue level with a predefined maximum. Note that this approach is applicable only to those models which redefine task priorities at each time increment since the need for (and hence the priority of) a rest period is a function of the length of time from the previous rest period.

The TRW approach keeps track of "metabolic limits" and compares these limits to some predefined level though it is not clear from References 3 and 4 how these continuously varying limits could be used with the window-filling time-lining technique. General Dynamics' OPTIMA model also recognizes the need to account for human factors. It does so however by providing analyses which optimize the crew's work/rest cycles.

4.0 Discussion and Recommendations

Each of the models discussed above was constructed to satisfy a unique set of requirements; as a result there is a wide variation in their characteristics and capabilities. Any new scheduling model that may be developed in the future should incorporate the desirable features of those already in use. This section presents the writer's recommendations on several features deemed desirable in a scheduler. It is hoped that they will provide insights that will contribute to formulating the objectives and requirements of any new model.

4.1 Model Construction

As described in Section 2.0, all the models surveyed are organized into three distinct areas: Data Preparation, Scheduler, and Output. It is recommended that any new scheduler be similarly organized. The primary advantage of this organizational structure is that the algorithm in each area can be almost entirely isolated from the rest of the model which facilitates changing the algorithm if desired. Since the optimum techniques for performing each of these primary functions have not yet been established, this capability would facilitate the incorporation of new techniques or permit the evaluation of competing techniques. In addition, the interfaces between areas provide convenient points for intermediate evaluations and outputs (e.g., General Dynamics' Space Station Mission Simulation Model).

4.1.1 Computation Options

The model should be capable of handling two types of problems: (1) the scheduling of an experiment package within fixed limitations placed upon mission duration and spacecraft/crew capabilities; and (2) the determination of the mission duration, and spacecraft/crew capabilities required to successfully schedule a fixed package of experiments or crew tasks.

In conjunction with this capability it would be advantageous to construct the model so that it could perform a variety of analyses both before and after the actual activity timelining computations. Pre-timelining computations would be used primarily where fixed limitations have been imposed on mission duration, spacecraft, and crew. The computations would indicate if there were discrepancies between overall capability and task requirements that would prevent scheduling of the entire package as defined. An example of a discrepancy would be a required amount of an expendable in excess of the amount available.

Post-timelining analyses should include options to perform a variety of analyses on the actual timeline. These would include timelines of crew activities and expendable consumption, and analyses of timeline efficiency. Another option might be to perform a contingency analysis, similar to those in Boeing's Heuristic Timeline Program and General Dynamics' Space Station Mission Simulation Model, to study the effect of random events upon the nominal timeline.

4.1.2 Data Input

All of the models require virtually the same input information. This information can be divided into the five general types of data shown in Table 8. There is however no standard method of either quantifying or tabulating the data characteristics within each type. The result is that each model has a unique method of quantifying the information and supplying it to the program.

Recently, the amount of experiment and subsystem data for the AAP mission has become so large and the characteristics so diverse that interest has been generated in developing computerized "data banks" to serve as centralized sources of information. Such data banks would contain complete descriptions of all pertinent systems and operations, and would be updated regularly so that the contents would reflect the latest design information. One of the major portions of such a development is the classification and quantification of design data so that it can be stored in a computer. The data bank approach could provide a single centralized source of design data. In addition, the data classifications developed for a data bank could, if widely accepted, evolve into a program-wide standard facilitating communication between the generators and the users of the data. Its potential is of particular interest here in that the existence of "standard" data classifications would affect the type and format of input information supplied to the scheduler.

One approach to such a data bank, designed specifically for AAP experiments by Martin Marietta/Denver Division (under contract to MSFC) is already operational.* It contains 66 experiment descriptors for each experiment and is currently used to "track" 73 experiments. Martin has not used the data

* Reference 8

TABLE 8
TYPES OF INPUT DATA

- Ephemeris Data
- Experiment Requirements and Constraints
- Spacecraft System and Subsystem Capabilities and Limitations
- Personal Activity Schedules
- Spacecraft Housekeeping Task Schedules

bank output directly as an input to their scheduling model (SAMMIE) because some of the data required by the scheduler is not easily quantifiable. The data classifications used by the Martin data bank should be studied more closely to determine which of them can be used for supplying data to a scheduling model.

4.1.3 Internal Data Libraries

As noted above, a large amount of input data is required by an Activity Scheduling Model for each run. Large amounts of this data however may not change from run to run. It is recommended therefore that the input data libraries be either an integral part of the program, or stored on a magnetic tape which can be easily read into the computer. In either case, the execution of the program would begin with the transfer of the required data from the permanent libraries to an active file. The input data deck would be read in after this transfer and would contain new values for any desired variable(s) in the active file. The appropriate variables in the active file would be redefined by the value defined in the data deck while the values of these same variables stored in the permanent data library would be unaffected. A similar arrangement is used in BCMASP and has proven quite satisfactory.

4.1.4 Spacecraft Ephemeris

All of the models require spacecraft ephemeris information. As suggested in Section 3.1.3 however, it would be more efficient to supply this information as input to the model rather than to generate the ephemeris within the model. For example, recent modifications to the BCMASP Earth-Orbit Simulator^{*} permit an eight month spacecraft ephemeris to be stored on tape. Such an ephemeris can be generated once, stored on tape, and used as input data to an activity scheduling model as often as desired.

The AAP core program is divided into distinct manned phases separated by dormant unmanned phases. Each manned phase will have its own experimental program. For purposes of crew-time planning, the core program may be considered as three separate missions (AAP-1/AAP-2; AAP-3A; AAP-3/AAP-4). Since the length of simulated mission time that can be stored on a single tape depends upon the amount of information to be stored at each recording interval,^{*} it would be useful to generate a new ephemeris tape for each manned phase. Doing so would permit a marked increase in the number of variables which may be stored at each recording interval and would enable such data as ground-site visibility, ground-station contact, and spacecraft day/night cycles to be stored along with the basic position, velocity, and time data.

^{*}Reference 13

This approach would also apply to missions beyond AAP in which earth-orbital space stations, logistically resupplied at intervals of a few months, are being projected. Crew rotations and equipment changes at points of logistic resupply may make sufficient changes in the space station to warrant considering the interval between resupplies as a mission.

4.2 Scheduler Algorithm

There appears no distinct advantage to using either the window-filling or the sequential scheduling technique. The latter has the capability to reflect changes in task priorities and so can be more easily responsive to dynamic crew factor problems such as fatigue but, as described above, the tasks are not necessarily scheduled in the defined order of priority. The window-filling method does schedule in order of priority but in three of the models* only one 24-hour period can be considered at one time. Though this simplifies the model it places an artificial barrier on its flexibility. Both methods will have to be studied in more detail before one can be recommended.

4.2.1 Nominal vs Operational Timelines

Both scheduling methods generate the same type of information; a set of crew timelines in which each task is assigned a specific start and stop time. Whether or not this approach will be suitable for future activity scheduling models depends upon the uses to which the output timeline will be put. If it is to be used as a mission planning tool to verify that all of the tasks can indeed be scheduled and/or to provide a guideline for the actual performance sequence of these tasks, then this approach will be satisfactory. However, if the timeline is to be used as an operational schedule, one that the crewmen are expected to follow, then an algorithm which more closely approximates realistic conditions may have to be found. For example, such an algorithm might not attempt to generate precise minute-by-minute timelines but rather might present the crewmen with groups of tasks (experimental, housekeeping, and personal) which would have to be performed in a given amount of time, e.g., 8-24 hours. The sequence of performance could thereafter be left to the crewmen, the only exception being those tasks whose time of performance is tightly constrained.

* MSFC/Brown Engineering's Experiments Scheduling Program, TRW's Experiments Scheduling Program, and General Dynamics' Space Station Mission Simulation Model

Such an operational timeline might improve crew performance by permitting crewmen much greater participation in the decision-making processes of the schedule, thereby stimulating their interest. In AAP-3/AAP-4 the performance of the ATM experiments are, to some extent, scheduled in this way.

4.2.2 Consideration of Human Factors

The impact of human factors on the generation of crew timelines increases significantly with increases in mission duration; a realistic algorithm should attempt to simulate the effects of these factors. Since their primary impact on the algorithm is through the rules governing crew work and recreation cycles, it is recommended that these rules be continually reexamined to keep them consistent with the most recent knowledge available.

Two examples of the type of effort being expended in the human factors area are found in References 15 and 16. Both studies examined the problems of performance during confinement and reported the following results:

- a. Men in confinement prefer work to free time and hence meaningful work opportunities are preferable to excess off-duty time.
- b. If contingency time is allocated in crew timelines, alternative tasks should be designated in the event that these contingencies do not occur.
- c. In many cases a 4/4 work/rest cycle (4 hours on - 4 hours off) appears preferable to the normal 8 hour work shifts, especially when the tasks are not intrinsically interesting.
- d. Task rotation should be considered as a normal routine. Note however, that task rotation is incompatible with the concept of specialized crew skills.

4.2.3 Determination of Task Priorities

Regardless of which scheduling method is used, all tasks are scheduled in descending order of priority. However, the criteria as well as the method for assigning these priorities varies considerably from model to model. In extremely simple cases the tasks may be input to the model in exact order of priority. In most cases however the tasks are first grouped by type (i.e., personal, system housekeeping, experimental, etc.) and then scheduled in a predefined sequence by the model.

In the models surveyed, experimental tasks are considered to have the lowest priority and so all other tasks are scheduled before the experiment tasks are considered. The major challenge to the scheduler is therefore to make the most effective use of the remaining time.

The experimental tasks are also considered for scheduling in descending order of priority (though they may not actually be scheduled in that order when the sequential timelining method is used). Although the answers to the question of what constitutes the most effective use of time are subjective, they are quite important since they are the primary determinants of the criteria used to assign priorities to the experimental tasks. As indicated above, a number of different criteria have been used including such experiment characteristics as experiment weight, experiment volume, performance time, crew time, and number of repetitions required.

One model^{*} requires that each experiment be given a rating to indicate its relative scientific merit or overall value to the mission. The rating is then used as the scheduling criterion.

Two of the models[†] that use the sequential method of scheduling use a combination of static and dynamic priority ratings for each experiment to revise the task priority list at each iteration. The static priority rating for each experiment is provided as one of the experiment descriptors. The dynamic rating is calculated at each iteration and depends upon current status of the spacecraft systems and crew requirements. These ratings are then combined (usually by taking their product) and the experiments reordered. It is apparent however, that these values as well as the other criteria mentioned above, are quite arbitrary and depend for the most part on the user's objectives and opinions. Though these rating methods should be given further study it is quite probable that no method will prove clearly superior to the others. It is suggested therefore that the computations for ordering tasks be kept as isolated as possible from the rest of the model so that different methods can be used as desired (perhaps even on option) with little or no modification required to the rest of the model.

^{*}MSFC/Brown Engineering's Experiments Scheduling Program

[†]General Electric's CASP and General Dynamics' OPTIMA

5.0 Summary

A comparison of seven activity scheduling models shows that they have definite similarities in overall structure and in their approach to scheduling. All of the models are organized into three distinct functional areas: Data Preparation, Scheduler, and Output. In addition, all use one of two time-lining methods: window-filling or sequential scheduling. Neither of these methods appears to have a distinct advantage over the other. The sequential method schedules a task in each free segment of mission time in sequence from the beginning to the end of the mission. At the beginning of each free segment of time, all of the candidate tasks are examined in descending order of priority and the first task whose requirements are compatible with existing conditions is scheduled. A noteworthy feature of this approach is its adaptability to the use of a dynamic priority rating. The priority of each unscheduled task is reevaluated at the beginning of each iteration so that all priorities are continually influenced by the timeline that has already been generated.

In the window-filling technique, the priorities for all tasks are established only once (a static priority rating) before the scheduling process begins.* Tasks are then scheduled in descending order of priority anywhere over the duration of the mission where the task requirements are compatible with the existing conditions. Some of the models that employ the window-filling technique consider only one 24-hour period at a time which appears to be an unnecessary limitation that severely reduces the flexibility of the approach.

Though there are only two methods (static and dynamic) of assigning priorities to each task, the criteria by which these priorities are assigned is different in each model and in all cases appears quite subjective. Among the criteria used to determine experiment task priorities are such objective characteristics as experiment weight, experiment volume, performance time, and crew requirements. Subjective characteristics such as scientific merit and "utility value" are also used.

Another major difference between the models is the method of quantifying task requirements and spacecraft/crew characteristics. Differences arise because much of the data, especially in the scientific area, is ambiguous and not easily quantifiable. Recently however there has been considerable

* There appears no reason why static or dynamic priorities cannot be used with either sequential or window-filling scheduling algorithms.

interest generated in developing computerized "data banks" to serve as centralized sources of information for all AAP data. Progress on the development of data banks should be followed, particularly in the area of data classifications which may affect compatibility with an activity scheduler.

Because of the uncertainties in so many of the basic areas (input data classifications, establishment of task priorities, and scheduling algorithms), it is recommended that any new model be constructed in such a manner that each of these basic functions is "isolated" from the rest of the model. This construction would facilitate evaluation of different techniques in each area as well as minimizing the problem of changing a particular technique at a later date.

Other recommendations include:

- a. Establishment of data libraries within the scheduler in order to simplify the input data deck.
- b. Generation of ephemeris data independent of an activity scheduling model where the capability to generate such data already exists, as in the BCMASP Earth-Orbit Simulator.
- c. Using a scheduling algorithm based upon mission rules that are sensitive to human factors considerations.

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